Statistical Properties of Elemental Abundances in Solar Analogs and the Possible Link to Planet Formation

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INTRODUCTION

High precision spectroscopy reveals that the sun has an unusual elemental composition relative to nearby solar analogues. In particular, the sun shows a depletion in refractory (rock-forming) elements by up to 10% when compared to more volatile elements. Furthermore, the magnitude of the depletion increases with the condensation temperature (T_c) of each element, suggesting a potential signpost of planet formation. The standard tool for detecting solar-like depletions in nearby stars requires the determination of elemental abundances to high precision, since the expected shift is of order 0.05 dex. Consequently, the typical sample size includes a small number of stars (~20). We attempt to measure the depletion trend using a novel statistical statistical approach with comparatively low signal-to-noise elemental abundance measurements from APOGEE-2 DR16. Our likelihood based analysis is able to place constraints on the overall distributions of elemental abundances in solar analogues, rather than relying on the statistics of individual stars.

MODELING

- The model is inspired by our previous work in which we detected debris disks at submillimeter wavelengths in the *Planck* CMB maps [1].
- We utilize a hierarchical mixture model, schematically illustrated in Fig. 1. The model allows for two populations of stars: depleted and not depleted. We suppose that all stars have [X/Fe]-T_c trends that are captured by the relation [X/Fe] $= mT_{c,X} + b + e(X)$, where e(X) is a random variable encoding both the intrinsic scatter and instrumental uncertainty in the abundance measurement for element X.
- At every level of our model we assume normality, with the slopes (m) following a normal distribution with mean and variance μ_m, σ_m^2, respectively. The intercepts (b) are similarly treated as normal random variables, with mean μ_b and variance σ_b^2.
- Since the [X/Fe]-T_c trend is expected to be different for depleted stars (D) vs. not depleted stars (ND), we allow the distribution of slopes and intercepts to have different underlying parameters for both populations of stars.
- The frequency of depleted stars is captured by the parameter f, while the ND frequency by (1-f).
- The last two levels of the model include two layers of variance, with the observed data for star *i* and element *j* being normally distributed with mean $mT_{c,X} + b$ and variance $\sigma_j^2 + \sigma_{N,ij}^2$. σ_j^2 represents the intrinsic scatter in element j, and $\sigma_{N,ij}^2$ is the APOGEE provided instrumental noise.
- The parameters to be determined include f and two sets of $\theta = \{\mu_m, \sigma_m^2, \mu_b, \sigma_b^2, \{\sigma_j^2\}\}$ — one for the depleted stars and not depleted stars.

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References:
[1] J. Nibauer, E. Baxter, B. Jain, 2020, AJ, 159, 5
[2] Jönsson H., et al., 2020, Arxiv: 2007.05537,
[3] I. Ramírez, J. Meléndez, M. Asplund, 2009, A&A, 508, 1.

SIMULATIONS

We test our pipeline on simulated data to ensure its proper functioning. We choose realistic values for all parameters, taken from the literature when possible. In order to ensure realistic levels of noise, we sample directly from the APOGEE provided uncertainties for the same population of stars in the results section. Results on simulated data are shown in Fig. 2, where the true parameter values are given by the dashed lines. For this simulated trial, we use 1000 stars and 4 elements.

Fig. 2

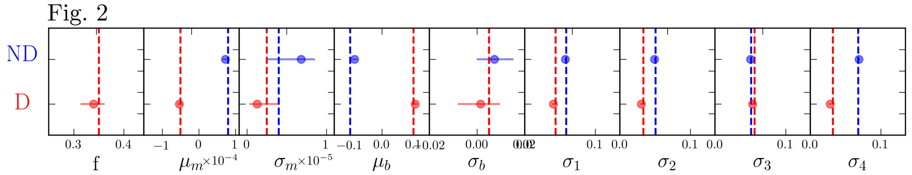


Fig. 3

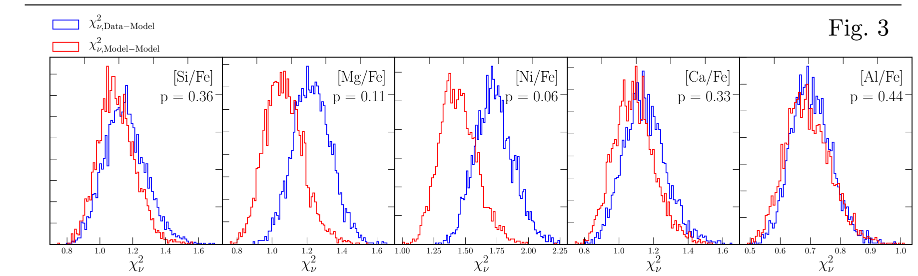
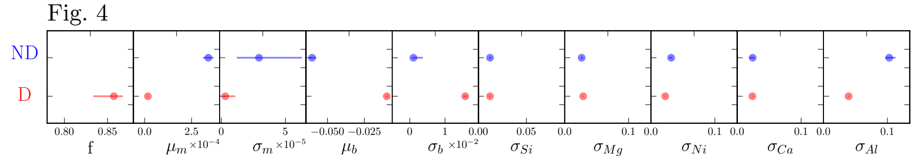


Fig. 4



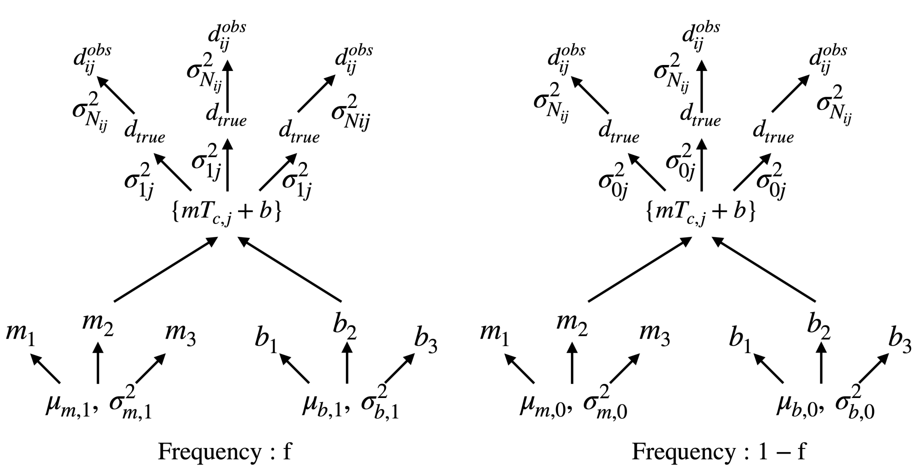
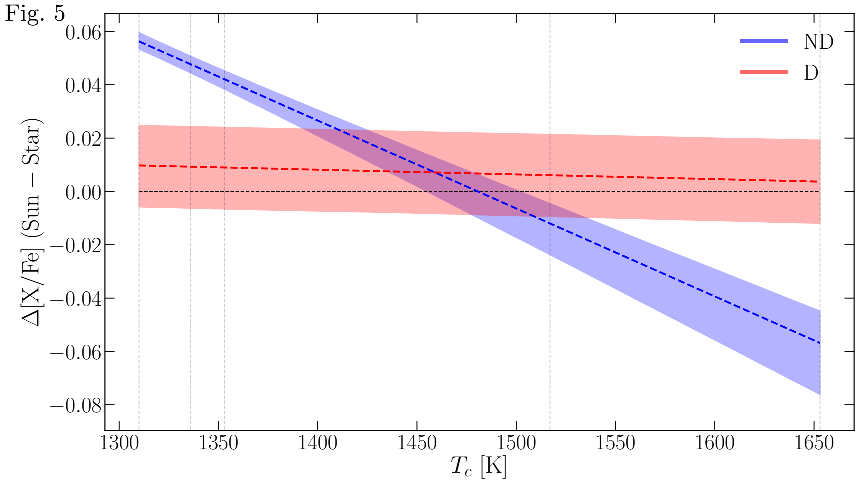


Fig. 1

DATA REDUCTION

- We rely solely on the [X/Fe] tag columns in APOGEE DR16 for abundance measurements, since these columns are only populated for the most reliable stars.
- We select for solar analogues as defined by $|[Fe/H]| < 0.1$, T_{eff} within 195 K of solar, log g within 0.1 dex of solar, and distance < 350 pc.
- We employ a 2σ outlier rejection on data to ensure that the tails of the distributions are not driving the fits. This is reasonable, since the difference between depleted and not depleted stars is small and should not significantly impact the tails of the abundance distributions.
- The remaining number of stars is ~ 1500.
- We run our analysis on a set of high T_c elements since the differences between D/ND stars are thought to be most extreme in this regime.
- Initial results are presented for Si, Mg, Ni, Ca, and Al. These elements are chosen for reliability, based on the discussion presented in section 6.10 of [2].

Fig. 5



RESULTS/DISCUSSION

- **Goodness of fit:** In Fig. 3, we test the model fit with a posterior predictive check, using the χ^2 as our test statistic. $p \geq 0.06$ for all elements, indicating a strong fit.
- **Constraints:** In Fig. 4 we present constraints on all model parameters. We find that $\sim 80\%$ of stars are distributed according to the depleted component of the model. We note, however, that our results are consistent with the notion that the sun is depleted in refractory elements relative to the majority of solar analogs. This is because while the depleted slope mean is near solar (i.e. m = 0), there is still a statistically significant preference for slightly positive [X/Fe] vs Tc slopes. Consequently, the Sun appears somewhat anomalous (i.e. refractory depleted) relative to the average solar analog.
- **Depletion Trend:** In Fig. 5, we plot realizations from the model for each step in the MCMC parameter chains. The vertical dashed lines correspond to the condensation temperature of the elements used. Note that the y-axis is Sun - Star. The ND band highlights a population of stars which are refractory enriched relative to the volatiles, while the D band highlights a population of stars with *near solar* abundances.
- **Comparison with the Literature:** Our constraints on μ_m for D and ND stars are in agreement with measurements of nearby solar analogues presented in [3]. Additionally, we find evidence of a bimodality in the abundance data also discussed in [3] for a smaller sample of stars, with some slopes taking on more negative values than others. We also recover the disputed solar depletion trend previously discussed.
- **Unique Approach:** Our novel approach for placing constraints on noisy abundance data has bright prospects for future spectroscopic surveys, and provides a new avenue to study the planet-star connection for large populations of stars.